Airborne Measurements of Oceanic Wind Vector Fields Over the Labrador Sea Using Passive Polarimetric Radiometry

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LONG-TERM GOALS

The focus of this research is to develop algorithms and aircraft and satellite remote sensing systems for imaging of ocean surface winds using passive microwave radiometers. The application of passive radiometry to ocean surface imaging, specifically using polarimetric microwave measurements of the third and fourth Stokes' parameters, has been identified as a potentially useful and low-cost means of obtaining the magnitude and direction of near-surface winds from space. The purpose of this work is to empirically characterize the polarimetric thermal emission signature from a wind-driven ocean surface using airborne measurements and to use the measured data to develop a theoretical emission model adequate for the prediction of satellite signatures at all wind speed ranges. A related goal is to understand the effects of air-sea stability and wind fetch on passive microwave emission signatures and to develop retrieval algorithms for ocean surface parameters, including ocean wave spectra.

OBJECTIVES

During the past grant period (October 1, 1997 through September 30, 1998) the primary objective of this work has been the analysis of data observed using the Polarimatric Scanning Radiometer on the NASA P-3 aircraft during the Labrador Sea Deep Convection Experiment[2] in March, 1997 [2,3]. As configured for the Labrador Sea experiment, the PSR consisted of a gimbal-mounted set of tri-polarimatric (three Stokes' parameter – $T_v = <|E_v|^2>$, $T_h = <|E_h|^2>$, and $T_U = \mathrm{Re}<E_v E_h^*>$) radiometers with operating frequencies near the important atmospheric transmission windows of 10.7, 18.7, 37.0, and 89.0 GHz [4]. The primary application of the PSR during the experiment was the generation of a database of high-resolution polarimetric, conically-scanned images of the wind-driven ocean surface under a variety of sea, fetch, and atmospheric states. The scanning geometry offered by the PSR provided unique radiometric observations around a full azimuthal scan of 360^o at several fixed cone angles, including the SSM/I incident angle of 53.1^o.

Questions to be answered using the PSR Labrador Sea data included: (1) What are the frequency and wind-speed dependencies of the observed azimuthal harmonic signatures? (2) What are the relative impacts of foam, wave asymmetry, and resonant thermal emission on the wind signatures? (3) What are the impacts on the azimuthal harmonic signatures caused by clouds and water vapor? (4) What is the impact of fetch and stability on the azimuthal signatures? (5) Do the wind signatures observed from

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2. A description of the Labrador Sea P-3 experiment can be found in reference [1], and a description of the PSR and copy of reference [1] can be found at http://www1.etl.noaa.gov/radiom/psr.html .

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aircraft correlate with those observed from the SSM/I instrument? (6) What is the utility of a two-look (fore and aft) method for determining the wind vector at a given pixel?

A secondary objective was the continued operation of the PSR during additional flight opportunities using upgrades of the PSR scanhead to provide measurements of the both the third and fourth Stokes parameters under extremely high wind conditions. Strategies for performing the measurement of the third and fourth Stokes' parameter vary, although there are essentially three viable techniques: (1) adding analog correlation, (2) analog multiplication, and (3) digital correlation. The first version of the PSR scanhead employed digital correlation ("PSR/D") and demonstrated this technique for passive Earth polarimetry for the first time. Due to interest in obtaining measurements of the fourth Stokes parameters as well as in obtaining direct experience with all types of correlators, an objective during the upgrade of the PSR was to develop analog polarization correlators ("PSR/A") for measurements of the third and fourth parameters. In addition, since the impact of water vapor on the azimuthal harmonics is of concern, an objective of the upgrade was to include a 21.5 GHz water vapor radiometer in the PSR/A scanhead.

APPROACH

The PSR aircraft data from the Labrador Sea Experiment required several levels of processing before the data could be interpreted as absolute calibrated brightness temperatures. Accordingly, a general purpose processing system was written in Matlab to perform the following functions: (1) merge and resample the various raw data streams of significance, including radiometric counts, scanhead angle position, calibration load temperature, and aircraft attitude, (2) calibrate the data using both sky looks (obtained during steep aircraft rolls) and periodic looks at hot and ambient blackbody targets. A unique nonlinear Wiener filter calibration algorithm was tailored for this process, (3) account for the effects of the nonlinear relationship between the digital correlation signal and T_U, (4) correct for antenna beam angle variations and polarization basis rotation caused by small aircraft rolls and pitches, and (5) correct for scan bias resulting from systematic variations in slipstream-induced vibration as a function of scan angle. The above processing was performed on all Labrador Sea PSR data, and the data was subsequently analyzed for wind-related azimuthal harmonic variations.

In addition to the Labrador Sea data, the PSR was flown on the NASA DC-8 as part of the Third Convection and Moisture Experiment (CAMEX-3) during August-September 1998. CAMEX-3 included several flights over severe convection and hurricane eyewall regions and provided a unique opportunity to augment the existing PSR Labrador Sea data with observations over extremely high wind cases (35-80 m/sec). Due to interest in observing possible azimuthal brightness temperature variations in the fourth Stokes' parameter ($T_V = \mathrm{Im}\langle E_v E_h^* \rangle$) the original PSR scanhead (PSR/D) was prepared for CAMEX-3 by including analog in-phase and quadrature-phase correlation channels on the 10.7 and 18.7 GHz channels. (The new scanhead is referred to as PSR/A.) Also, due to interest in understanding the effects of signal variations caused by water vapor variations the PSR/A scanhead included a 21.5 GHz water vapor radiometer. This radiometer shared the same antenna as the existing 18.7 GHz radiometer. Finally, the PSR/A scanhead included internal noise diode calibration circuitry on all radiometers. The new circuitry allows estimation of the radiometer gains and offsets at intervals of ~0.5 seconds as compared to 15 seconds for the old system, thus reducing the effects of flicker noise considerably.

WORK COMPLETED

The above-described data processing steps resulted in approximately 25 hours of calibrated brightness imagery with an absolute error (i.e., bias) of less than 3-10 K (depending on channel) and with a typical radiometric resolution (ΔTrms) of 1-2.5 K per 25-msec sample. Data during several Labrador Sea hex-cross maneuvers have been used to corroborate the azimuthal wind direction harmonics observed using the SSM/I instrument, with excellent agreement being obtained (Figure 1) for 12-15 m/sec wind speeds. The measured azimuthal harmonic amplitudes were also analyzed for wind speed dependence (Figure 2), with reasonable agreement obtained between the PSR and SSM/I data. Also demonstrated using the Labrador Sea data were high-resolution wind vector maps using a maximum likliehood estimator algorithm.[3]

The upgraded PSR/A system was flown during CAMEX-3 for a total of ~100 flight hours. The CAMEX-3 data set provided eyewall crossings of Atlantic hurricanes on six separate flights, and over 40 hours of data at wind speeds greater than ~30 m/sec. Processing the CAMEX-3 data set has required the development of T_U and T_V calibration algorithms to account for the crosstalk from the linearly-polarized channels inherent in all analog adding correlators. A polarized blackbody calibration target [5] was used to calibrate the PSR polarimetric channels prior to flights during CAMEX-3.

RESULTS

The agreement between the PSR Labrador Sea azimuthal harmonics for wind speeds in the 12-15 m/sec range is excellent for the frequencies and polarizations available from SSM/I wind vector studies (37 GHz, v and h) . The first harmonic is dominant in the T_v data, and the second is dominant in the T_h data. The T_U data is comprised of both first and second harmonics of significant strength although the relative strength of the second harmonic is greater at 10 GHz than at 37 GHz. Overall the data suggest a small variation of harmonic amplitude with frequency, the amplitudes being ~10-50% higher (depending on polarization) at 37 GHz than at 10 GHz. Nonetheless, the 10 GHz signals appear to be reasonably strong with respect to typical radiometric precisions and thus useful for wind direction sensing. The 10 GHz harmonic amplitudes – especially T_v – also appear to be increasing with wind speed at the high range of the data (20 m/sec) while the higher frequency harmonics tend to exhibit amplitude saturation at that wind speed. The result suggests an increased utility of the 10.7 GHz data in high wind speed conditions. Finally, it is noted that the T_U harmonic amplitudes appear to be consistent with calculations based upon an asymmetric wave model of the ocean surface [ref. 6, p. 153].

It was also found (not illustrated) that the T_U data are significantly less affected by the presence of clouds and convection than T_v or T_h. It is hypothesized that clouds and/or local hydrodynamic modulation caused by inhomogenities in the marine boundary layer momentum fluxes at meso-beta spatial scales (~10 km) can significantly perturb T_v and T_h harmonic measurements, but much less so for T_U and T_V.

The upgraded PSR/A system now includes internal noise diode calibration at ½-second intervals (an improvement of 30x compared to the previous calibration interval of 15 seconds for PSR/D), a 21.5 GHz water vapor channel with both vertical and horizontal polarization, and analog quadrature hybrid adding correlator circuitry for the measurement of the third Stokes parameter T_U at 10.7, 18.7, 37.0,

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3 See reference [7] for a presentation of the first high-resolution passive microwave wind vector map.

and 89.0 GHz and the fourth Stokes parameter T_V at 10.7 and 18.7 GHz.[4] A block diagram showing the layout of a typical PSR/A radiometer (the 18.7/21.5 channel pair) is shown in Figure 3.

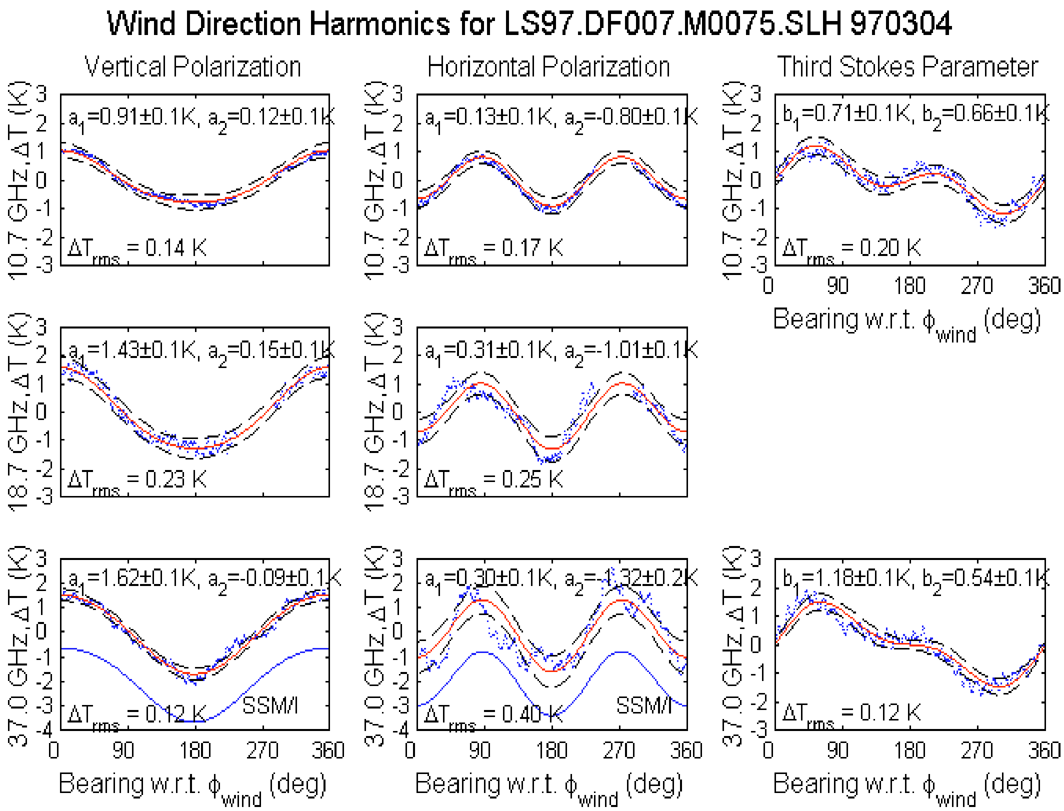

Figure 1. Wind vector azimuthal harmonics during hex-cross manuevers on March 4, 1997 over the R.V. Knorr during the Labrador Sea Deep Convection experiment. The SSM/I harmonics for 37 GHz v& h polarizations are shown displaced by –2 K for comparison.

IMPACT/APPLICATIONS

The development of the PSR airborne conical scanning radiometer system and its operation during the Labrador Sea campaign have proven the utility of airborne passive microwave wind vector sensing for high-resolution ocean surface studies. The Labrador Sea data have provided independent corroboration of the SSM/I harmonics amplitudes observed from satellite.and a geophysical model function for use in the design of the WindSAT and NPOESS CMISS satellite wind vector sensors. The data extend the SSM/I geophysical model function for wind vector harmonic amplitudes to the important bands down to 10 GHz and the third Stokes' parameter. The impact of clouds and local convection on the PSR data suggest that the polarization channels T_U and T_V will be relatively immune to the effects of clouds and convection, but that frequencies as low as even 10 GHz may be significantly affected, particularly on meso-beta spatial scales and during unstable conditions. The PSR system has also provided a pathfinder to an NRL airborne wind vector radiometer.

4. See the PSR web site at http://www1.etl.noaa.gov/radiom/psr.html for a description of the upgraded PSR/A instrument.

Once processed, the third and fourth Stokes parameter data over the CAMEX-3 hurricanes will provide a means of assessing the utility of passive microwave wind vector sensors for measuring wind speed and direction in the high-wind speed regime (>25 m/sec) where scatterometers begin to lose sensitivity.

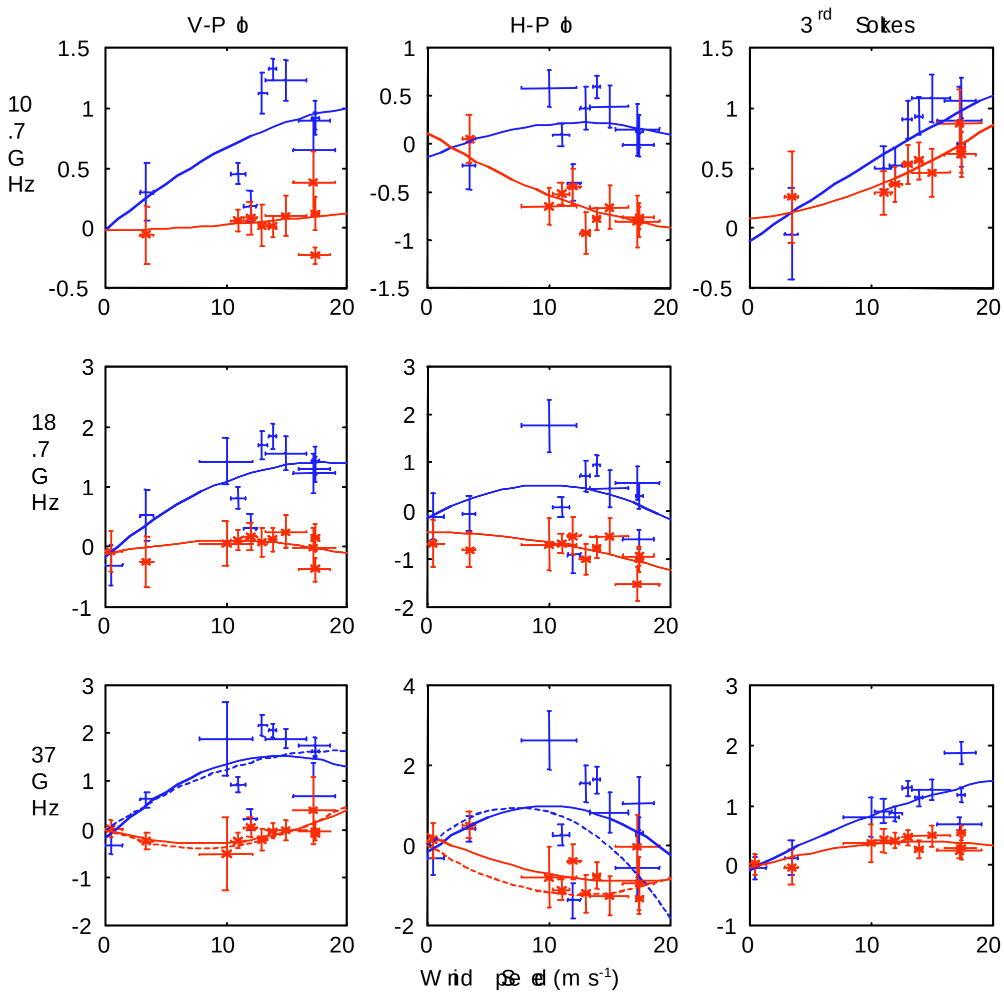

Figure 2. Wind direction harmonic amplitudes obtained from hex cross maneuvers during the Labrador Sea Deep Convection experiment: first harmonic (🕮) and second harmonic (🗀). The SSM/I harmonic amplitude coefficients for 37 GHz v and h polarizations are shown as dashed lines for comparison.

TRANSITIONS

The PSR/A scanhead and additional interchangeable scanheads (PSR/C, PSR/S) being built for use with the PSR positioner will be used for passive remote sensing studies during the 1998 NASA TRMM Kwajelein Experiment (KWAJEX), icing studies during the Mount Washington Icing Sensors Project (MWISP), and during proposed studies of the effects of convection in marine boundary layer stability during the 1999 ONR Shoaling Waves experiment.

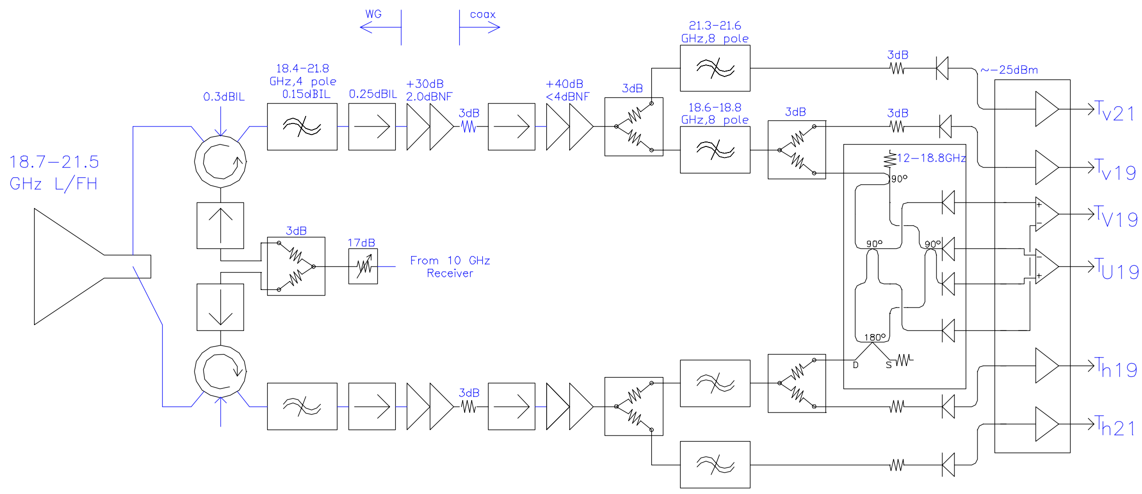

Figure 3. Block diagram of PSR/A 18.7/21.5 polarimetric radiometer as upgraded for CAMEX-3. The 18.7 GHz channels are fully polarimetric. The polarimetric channels T_U and T_V are implemented by adding correlators using balanced quadrature hybrid arrays for phasing.

RELATED PROJECTS

1 – The PSR/A system is being used in airborne studies of convective precipitation and hurricane evolution in the NASA CAMEX-3 and KWAJEX field campaigns.

2 – A deployment of the PSR/C system is planned for the summer of 1999 on the NASA P-3 platform in conjunction with the U.S. Department of Agriculture’s Southern Great Plains Experiment to remotely measure soil moisture.

3 – The PSR Labrador Sea data is being used to develop wind vector retrieval algorithms useful on the future NPOESS CMISS and WindSAT satellite instruments.

4 – The PSR Labrador Sea data is being used to study the relation between active and passive geophysical signatures of hydrodynamic modulation caused by convective instability. The study is being carried out jointly with Dr. J. Carswell of the University of Massachusetts at Amherst.

5 – The PSR Labrador Sea data is being used to demonstrate the possibility of retrieving ocean wave spectra using multi-angle radiometric observations of the ocean surface. This work was done in collaboration with NOAA/ETL visiting scientist Dr. Y. Trokhimovsky of the Space Research Institute in Moscow, Russia.

6 – The PSR Labrador Sea data is being used to develop a relationship between u* and passive microwave harmonic amplitudes in collaboration with Professor David Weissman of Hofstra University.

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